AD-A056 775 NAVAL OCEAN SYSTEMS CENTER SAN DIEGO CA F/G 13/10.1
POWER ELECTRONICS TECHNOLOGY APPLICATIONS FOR FUTURE SSBNS (BY --ETC(U)
JUN 78 J FOUTZ, E KAMM

UNCLASSIFIED NOSC/TR-177-REV-A NL

1 OF 1
ADA
056775

END
DATE
FILMED
9 78
DDC

LEVEL II

(1.2)

NOSC

AD A056775

NOSC TR 177
REVISION A

Technical Report 177
REVISION A

POWER ELECTRONICS TECHNOLOGY APPLICATIONS FOR FUTURE SSBNs

By using switching regulator power supplies in SSBN electronic systems, reduced costs and improved performance can be reflected in both the electronic and electrical power systems

J Foutz, E Kamm

1 JUNE 1978

Final Report

Prepared for
Naval Sea Systems Command

NAVAL OCEAN SYSTEMS CENTER
SAN DIEGO, CALIFORNIA 92152

NAVAL OCEAN SYSTEMS CENTER
SAN DIEGO, CA 92152

The enclosed Naval Ocean Systems Center Technical Report (TR 177, Revision A) replaces in its entirety the original TR 177 mailed to you in March 1978.

Please return all copies of TR 177 previously sent to you and replace them with the enclosed TR 177, Revision A.

Mail the TR 177 copies to:

COMMANDER
NAVAL OCEAN SYSTEMS CENTER
ATTN: CODE 9234 (J. FOUTZ)
SAN DIEGO, CA 92152

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NOSC Technical Report 177 (TR 177) Revision A #AD51 246	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) 6 POWER ELECTRONICS TECHNOLOGY APPLICATIONS FOR FUTURE SSBNs (By using switching regulator power supplies in SSBN electronic systems, reduced costs and improved performance can be reflected in both the electronic and electrical power systems)		5. TYPE OF REPORT & PERIOD COVERED 9 Final rep[redacted]
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) 10 J Foutz, E Kamm		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Ocean Systems Center San Diego, California 92152		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 63588N, 20787, ~~Q250~~
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Sea Systems Command Washington DC 20362		12. REPORT DATE 11 1 Jun[redacted]78
		13. NUMBER OF PAGES 44
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) 12 47 p.		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution is unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

14 NOSC/TR-177-REV-A

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Power supplies–switching regulators
Voltage regulators–SSBN
Converters–SSBN
Electric power–distribution on SSBN
Ballistic missile submarines–electrical power
Ballistic missile submarines–electronics power

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Conversion and use of electrical energy by electronic systems in present SSBNs are briefly described, along with problem areas in the present SSBN approach. As an alternative, a candidate electrical power system is proposed that is based on distributing either 160 or 270 V dc to electronic systems that use switching regulator power supplies for internal power conversion. The proposed technology has a potentially high leverage for achieving the SSBN goals of lower life-cycle costs, improved performance, smaller size, and less weight. Potential advantages over the present approach also include lower initial cost, more efficient cooling, lower power consumption, higher reliability, and superior performance. The several power electronic technological Over

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-LF-014-6601

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

393 159

Alt

20. Continued.

advances that are central to this approach could be beneficial to future SSBNs whether or not the alternative system, comprised of a dc source and switching regulator, is selected.

OBJECTIVE

Identify power electronic technologies which will provide improved cost-effectiveness in the conversion and use of electrical energy by SSBN electronic systems, either through reduced cost, improved performance or both.

RESULTS

1. A candidate electrical power system is proposed that is based on distributing either 160 or 270 V dc to electronic systems that use switching regulator power supplies for internal power conversion. This system is proposed as an alternative to that used in the present SSBN designs.

2. Powering all SSBN electronics by 160 or 270 V dc electrical input rather than 60 or 400 Hz ac input is a major change that, if implemented, would affect the SSBN electrical system and all electronic systems on the SSBN.

3. The proposed technology has a potentially high leverage for achieving the SSBN goals of lower life-cycle costs, improved performance, smaller size, and less weight. Potential advantages over the present approach also include lower initial cost, more efficient cooling, lower power consumption, higher reliability, and superior performance.

4. The several power electronic technological advances that are central to this approach could be beneficial to future SSBNs whether or not the alternative system, comprised of a dc source and switching regulator, is selected.

5. The major shortcoming of the proposed alternative is that it is a complex technology that appears to be simpler than it actually is. Because of this apparent simplicity, misjudgments are likely in the design and application of this alternative system by the uninitiated engineer.

6. The advantages of the proposed system are considered well worth exploiting, provided an agressive, concurrent risk-reduction program is conducted that identifies potential problems, develops solutions, makes information available to all contractors and design activities, and closely monitors designs and applications to circumvent potential problems.

RECOMMENDATIONS

Continue the study of this alternative to the point where sufficient information for a decision is available. Key questions to be resolved and activities to be performed are as follows:

1. Determine the impact of switching regulator noise on sensitive circuits, including low-frequency communication circuits.

2. Determine the impact of switching regulator noise on SSBN observables.

3. Determine the cost and benefit to a typical electronic system that would be obtained by powering it from a dc source.

4. Determine the cost and benefit to the electrical system that would be obtained by powering the electronic systems from a dc source.

5. Conceive a system design, identifying components and subsystems that need major development.

6. Demonstrate the utility of power processing modeling and analysis computer programs as risk-reduction and design tools.

7. Because adverse findings in recommendations 1 or 2 could totally negate the approach, at least for some electronic systems, and because the results of those two determinations would be applicable to present programs, pursue recommendations 1 and 2 immediately, with the highest priority.

CONTENTS

DESCRIPTION OF EXISTING SYSTEM

ELECTRICAL POWER SYSTEMS

Primary electrical power is generated by redundant ship's service turbine generator (TG) sets as 450 V, 60 Hz, 3 phase, Type I power sources (per MIL-STD-1399, section 103). This voltage is distributed to 450 V ac loads, and for other loads is reduced to 120 V ac or converted to 250 V dc (nominal) by means of motor-generator (MG) sets. In the dc system, dc voltage is distributed to the dc loads and for the 400 Hz loads is converted by seven motor generators, two of which are spares.

The dc system also maintains the main battery state of charge. If loss of the 60 Hz input to the dc MG sets occurs, the battery then supplies all the dc system loads. On the other hand, if loss of the TG sets occurs, these MG sets reverse function, running on battery power to generate power for the 60 Hz ac system loads.

Power system protection and control is provided by electromagnetic/thermal circuit breakers.

Almost all the loads that require 400 Hz input are electronic loads, which separately convert this ac input to various dc voltage levels for their internal use. A small amount of power at 400 Hz ac is used directly for some nonelectronic components such as fans and blowers.

POWER CONVERSION IN ELECTRONICS

Transformer-rectifiers are usually used in the baseline electronics to convert the ac input voltage to the dc levels used internally by the electronic circuits. If regulation is required, series dissipative regulators are used. Occasionally lossless regulators are used to increase efficiency. These include transistor switching regulators used after transformer-rectifiers, solid-state thyristors used in rectifier bridges, and ferroresonant transformers. However, the bulk of the ac-to-dc power conversion used in the baseline electronics is done by line-frequency transformers followed by rectifiers and filters and, if needed, series dissipative regulators.

ELECTROMAGNETIC COMPATIBILITY (EMC)

Submarines have unique EMC problems. Solutions to these problems in the baseline systems include reducing harmonic currents and voltages in the ac power system, keeping currents within intended wire runs and out of the hull, and separating and shielding cables. Other EMC problems caused by pulse loads make it necessary to isolate them from the power system. The detailed implementation of solutions to these EMC problems has considerable impact on the size, weight, and cost of power conversion circuits and subsystems.

PROBLEM AREAS

The baseline system presents several problem areas. These are discussed in detail to provide backbround information for the advantages of the candidate system. The problem areas discussed involve multiple power conversion stages, efficiency, pulse loads (sensitivity to transients and modulation), continuity of power, harmonic currents, structure currents, and system integration.

MULTIPLE POWER CONVERSION STAGES

Each stage of electrical power conversion requires equipment that adds system penalties in such areas as size, weight, cost, power consumption, cooling requirements, failure rate, personnel, training requirements, spare parts, etc. A system design objective should be that each user of electrical power accept electrical power as generated by the platform's main power source, and, if necessary, convert to special power requirements in a single stage. Exceptions to this general design objective should be made only after a careful trade-off is made of system penalties versus the benefits of an alternative approach. The baseline system, on the other hand, contrasts sharply with this idealized design: before being used by some electronic circuits (such as 5 V logic circuits), the 450 V ac 60 Hz is (1) converted to dc by a motor generator, (2) then converted to 400 Hz ac by another motor generator, (3) then, in a regulator, converted back to dc by a transformer rectifier and regulated by a series dissipative regulator, and (4) finally distributed to the electronic circuits. This multiconversion sequence is illustrated in figure 1.

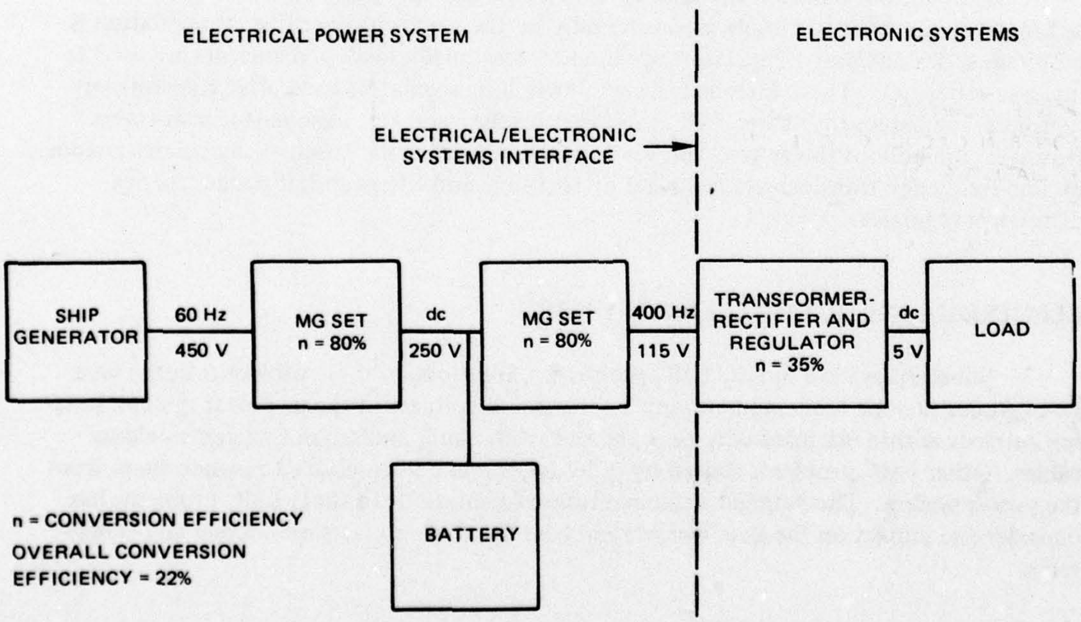
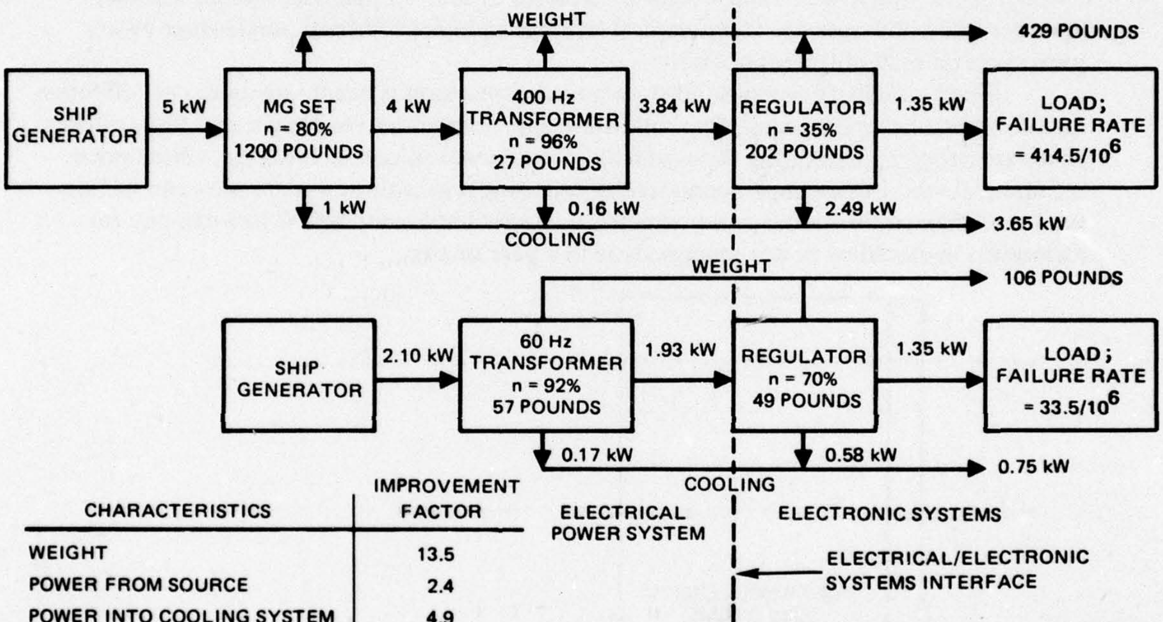


Figure 1. Power conversion stages–SSBN baseline.

The results of an earlier study[1] on the system impact of switching regulators on surface ships are shown in figure 2. As can be seen, this configuration is similar to the SSBN baseline except that a typical SSBN baseline has an extra MG set and no transformer in the electrical system. By going to a configuration similar to one of the candidate systems proposed in this report, the surface ship study showed the following power conversion subsystem improvement factors: weight, 13.5; source power, 2.4; power into the cooling system, 4.9; and reliability, 12.4. The efficiency of the surface ship configuration is 27%. This compares with only 22% for the SSBN baseline; thus the potential improvements in the SSBN should be even greater than these.



CHARACTERISTICS	IMPROVEMENT FACTOR
WEIGHT	13.5
POWER FROM SOURCE	2.4
POWER INTO COOLING SYSTEM	4.9
RELIABILITY	12.4

Figure 2. System impact of switching regulators–ships.

EFFICIENCY

As shown in figure 1, overall efficiency from the output of the turbine generators to a logic load in the baseline system is 22%. The other 78% of the generated power is lost in heat, which must be extracted by the cooling system with its associated size, weight, and power consumption. In at least one of the candidate systems to be proposed later, power conversion efficiency can be raised to 70%. Only 30% must be removed as thermal energy by the cooling system.

[1] NOSC Technical Document TD 107, Reduction of Shipboard 400-Hz Power Requirements–Cost and Technological Feasibility, p 56, by E Kamm and J Foutz, 16 May 1976

In the limit, efficiency savings can be used to approximate the savings in size and weight in solid-state systems. This is a valid approximation, assuming other things are equal (such as packing technology, cooling methods, and allowed upper junction temperature in solid-state silicon devices), because the volume required by the electronics is determined by thermal density limits (heat dissipated per unit volume) and the weight of a system is roughly proportional to its volume. Thus the weight and volume of the power conversion portion of the system in relationship to that of a unit load is 3.55 units for a conversion system having 22% efficiency and only 0.43 unit for one having 70% efficiency. This is illustrated in figure 3. Thus, going from 22% to 70% efficiency reduces the power conversion subsystem size and weight by a factor of 8.3 and reduces the combined load and power-conversion subsystem's size and weight by a factor of 3.2. In practice, factors will vary. However, they illustrate the technological leverage of high-efficiency, single-stage power conversion on system figures of merit.

Finally, high-efficiency solid-state power conversion is becoming more cost effective than conventional approaches. The solid-state approach conserves copper and iron, whose prices are rising, by exploiting the products of solid-state silicon technology, whose price is coming down. For example, commercial switching-regulator power supplies can be less expensive than conventional power supplies in power levels over 500 W and can pay for themselves in electrical power savings alone in a year or two.

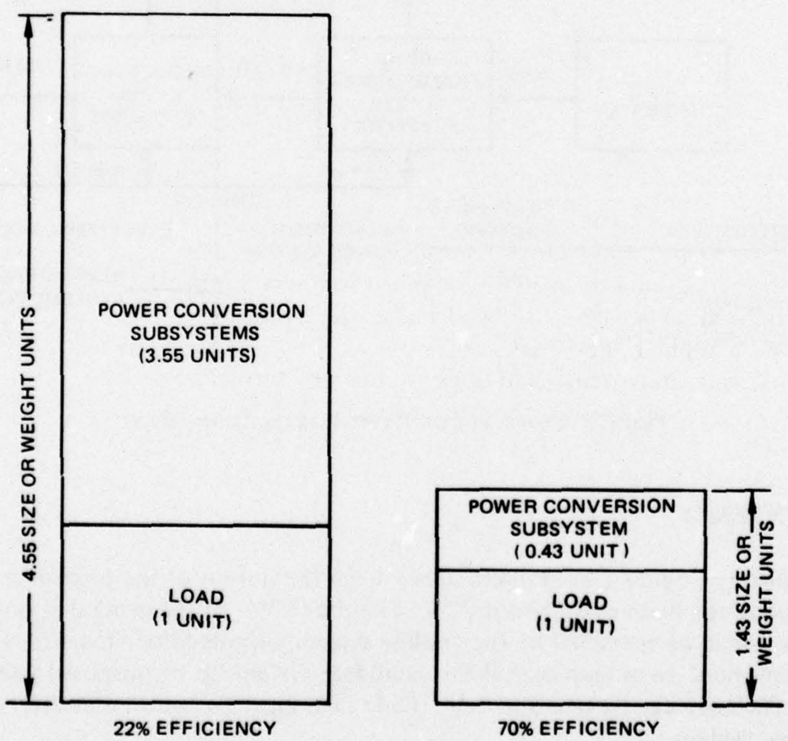


Figure 3. Size and weight comparison for systems having different efficiencies but equal thermal density.

PULSE LOADS (SENSITIVITY TO TRANSIENTS AND MODULATION)

The inherent response of a generator to a step change in load is a transient. To repetitive step changes in load the result is a modulation. This is shown in figure 4, taken from NOSC TD 107[1] (ibid, p 93). Dissipative regulators, used in the SSBN baseline, obtain

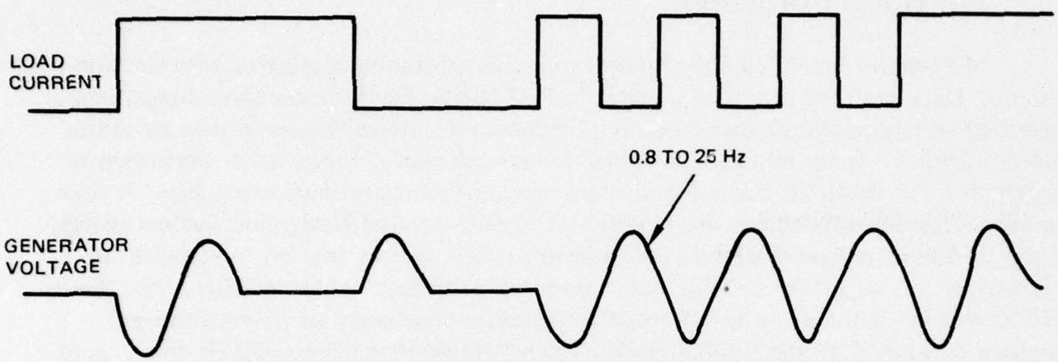


Figure 4. Generator response to load changes.

immunity to negative transients at the cost of decreased efficiency. The approximate efficiency of a regulator redesigned to operate through a negative transient is 100% minus the percent of the transient, multiplied by its basic efficiency (its efficiency before it was redesigned to handle negative transients). Thus a power supply with a basic efficiency of 40% will be lowered to 36% if designed to operate through a −10% transient (usual commercial limit) and will be reduced to 33% if designed to operate through a −18% transient. The substantial system penalties of low efficiency have already been discussed. To minimize these penalties, equipment designers usually design so that the equipment barely meets requirements with no safety margins or does not operate during normal transients. For example, transients down to −18% occurring several times daily are within the SSBN electrical power system specification limits. However, many of the SSBN electronic subsystems will not operate through these transients. For one reason, the general electronic specifications do not require operation through transients because the penalties of lowering efficiency to meet the transient requirement are considered excessive. The switching regulators proposed in the candidate systems, in contrast, can be designed to meet any reasonable transient limit with generous safety margins, no efficiency penalty, and very little penalty in any other design parameter.

Well designed regulators of both the dissipative and switching type can be designed to be immune to power line modulations. In fact, dissipative regulators usually turn out to be immune to them even if no thought is given to this behavior in the design. In most switching regulator configurations this is not true, and power-line modulation often will cause problems

unless careful consideration is given to desensitizing the design to it. Techniques for doing this have been developed[2,3] but may not be obvious to the uninitiated circuit designer, and marginal designs–including some on the baseline SSBN system–are needlessly common. Unregulated power supplies, almost without exception, pass source modulation onto the load at some frequencies.

CONTINUITY OF POWER

Momentary loss of electrical power can have substantial impact on ship electronic systems. Data from the results of a survey[4] of 37 Pacific Fleet surface ships concerning the effect on equipment of a momentary (3–30 second) interruption of power are reproduced in table 1. Many equipments subjected to such power losses suffer performance degradation for up to 20 hours before they recover full operational capability. A wide variety of mission capabilities are affected. The Ship Inertial Navigation System (SINS) is one of several critical systems in the baseline SSBN system that are susceptible to momentary loss of power and can have considerable impact on the mission. For these critical systems, a dc link is usually used to maintain continuity of power from an auxiliary dc source. In the baseline SSBN system, the 60 Hz-to-dc-to-400 Hz conversions form such a dc link, and the submarine 250 V battery is the auxiliary dc source. Providing for continuity of power in all ac systems is difficult. The baseline system uses complete system redundancy for the SINS. One of the advantages of the proposed candidate system is that it provides a dc link, at no system cost, that can be exploited in a variety of ways to maintain continuity of power to critical electronic loads.

Since this is a technology study for the future, a comment on the trends in electronic systems is appropriate. There is an overwhelming trend in electronics away from analog systems towards all-digital systems having digital signal processing that requires memory. For example, the use of microprocessor-based designs is increasing. These systems are more immune to general system noise, which switching regulators contribute to, but they are more intolerant to transient loss of circuit power, which switching regulators help mitigate.

HARMONIC CURRENTS

Harmonic currents are generated when a sinusoidal voltage is applied to a nonlinear load. Harmonic currents in electronic equipment are primarily caused by rectification of ac and by the magnetizing current of iron-core transformers and motors. The main effect of harmonic currents in an ac system is distortion of the ac voltage waveform through the source and distribution system impedance. The distorted waveform, in turn, can cause problems in poorly designed electronic equipment, increased power losses in motors and

---

[2] NASA CR-135072 (TRW 26629.000), Development of a Standardized Control Module for Dc-to-Dc Converters, by Y Yu, RI Iwens, FC Lee, and LY Inouye, Contract NAS 3-18918, 30 August 1977

[3] RD Middlebrook and S Cuk, Modelling and Analysis Methods for Dc-to-Dc Switching Converters, IEEE International Semiconductor Power Converter Conference, Orlando, Florida, 28–31 March 1977

[4] Chief of Naval Development, Naval Technology Projections, Part III, Advanced Systems Concept, Improved Continuity of Shipboard Power, 1 October 1971

TABLE 1. RECOVERY TIME OF SHIPBOARD ELECTRONIC EQUIPMENT TO POWER INTERRUPTIONS OF 3 TO 30 SECONDS.

Equipment Type	Time to return to operation, min	Time to achieve full equipment performance, min
ECM	3	60
Radar PPI	3	30
Sonar (FC)	5	5
Sonar	1-30	5-30
Radar (traffic control)	3-15	60
Navigation equipment	45-240 (0.75-4 hours)	60-1200 (1-20 hours)
Search radar	3-10	5-60
Processing equipment	1-180	180-300 (3-5 hours)
Radio communication	1-30	5-30

other magnetic devices, reduced torque in high-efficiency induction motors, and—most important in submarines—excitation of undesirable vibration modes through electrical-mechanical couplings. Furthermore, a distorted waveform can act as a driving source for submarine hull currents. For these reasons, recently revised specifications place a 3% limit on the amplitude of any harmonic current. Figure 5, from NOSC TD 107[1] (op cit, p 89), shows the relationship of the 3% limit to the harmonics generated by the normal six-pulse bridge rectifier circuit used in most electronic systems that are powered from a 3-phase source.

The approaches used to reduce harmonics include 12- or 24-pulse rectification, harmonic traps, and low-pass filters.

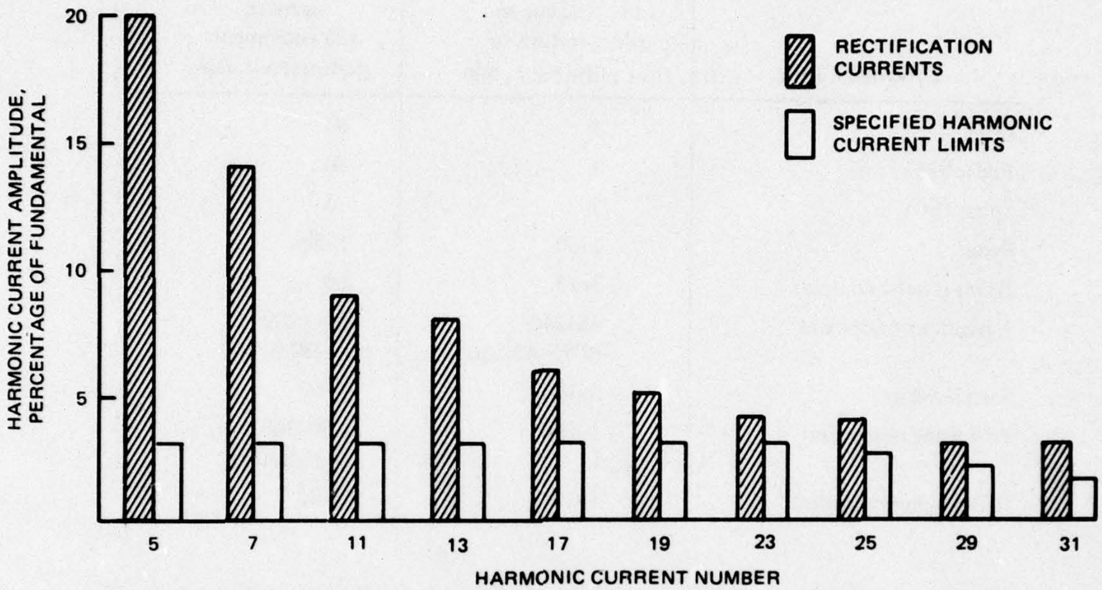


Figure 5. Harmonic currents caused by 6-pulse bridge rectification.

Additional harmonics are generated in systems having repetitive pulse loads. The pulse load modulates the rectifier "carrier" harmonics, to cause sidebands on each side of each harmonic.[5]

Of the two candidate subsystems proposed, one eliminates the harmonic current problem altogether and the other shifts it out of each individual electronic system into one or a limited number of points in the power systems.

STRUCTURE CURRENTS

The three-wire electrical system on the baseline system is the floating type. There is no intentional grounding to the structure, anywhere in the system, of any of the three power lines. However, capacitive paths exist between each of the power lines and the structure. Although stray capacitance is significant, most of this capacitance is from the lines to chassis capacitors in equipment EMI filters. In each equipment, these EMI capacitors form a capacitive-coupled ac local ground that varies in voltage from equipment to equipment. These local ground voltages are neutralized by current flow in the low-impedance ship's structure. These structure currents can flow through electronic equipment bonded to the

[5]NOSC TN 270, Simplifying a Difficult Harmonic Problem, JR Wilts, 31 October 1977. (NOSC TNs are informal documents intended chiefly for internal use.)

structure and in doing so can degrade sensitive equipment such as vlf couplers. They can also cause magnetic fields due to the loop area of the unintentional structure return path. Since the coupling is capacitive, the higher frequency harmonics, if present, provide a major driving source for such currents.

In the baseline system the solution to this problem is to limit the amount of capacitance to chassis in equipment EMI filters and to break up the current paths with isolation transformers. The two candidate subsystems proposed differ in how structure currents can be resolved. In the configuration that eliminates the harmonic current problem there is no easy way to isolate structure currents if they become a problem in system integration. The other configuration does allow flexibility in locating isolation transformers for controlling structure currents, but at the cost of returning the harmonic current problem to the baseline-system level of difficulty.

SYSTEM INTEGRATION

The combined electrical power subsystem and its load form a complex system with many potential interactions. The baseline system has experienced several of these interactions at various stages of system integration. The addition of electronic loads containing harmonic traps has made it necessary to readjust generator control loops to maintain desired stability. The addition of filters between the power source and electronic loads has affected the operation of some equipments by causing their input voltages to go out of tolerance when other loads are energized. Systems similar to the baseline system have had to add multiple isolation transformers late in the integration phase to control structure currents. High-efficiency power conversion, with its negative input resistance characteristics, can cause the whole power system to go unstable if it is not properly compensated.

The earlier in the design these types of potential problems are detected and corrected, the less the cost impact to the program. A recent project manager's guide for achieving low-cost electronics[6] looked at project successes and failures in industry and government. It found that 90% of total project costs are determined after only 10% of the funds are spent, that one reason for not achieving project goals was failure to manage risks, and that only 2% of the project managers interviewed were aware of any actions being taken on their program to reduce risks. In a gathering of electric power system and electronic system power supply experts representing the various Navy labs and centers working in the field,* one major conclusion was that both the tools and the data for proper integration of loads to the electric power system were inadequate and in need of much improvement. An EMC control plan[7] for the baseline systems also concludes that the earlier potential problems are identified, the more readily they can be circumvented to reduce program costs and schedule impact. The control plan contains a prediction and analysis methodology that formalizes the identification and correction procedure for potential EMC problems.

---

[6]NOSC TD 108, Project Manager's Guide, p I-1, by JH Townsend, 1 June 1977

[7]NAVSHIPS 0900-078-1010, TRIDENT Submarine Command and Control System EMC Control Plan, section 6 and appendix C, Rev C, 10 October 1975

*TESSAC EM-Power Workshop, Naval Research Laboratory, Washington DC, 15-17 March 1977

Existing tools and techniques for system integration are as follows:

A single equation in the NAVSEA/NAVSEC Ship Design Synthesis Models, the load power analyses[8]

A method for determining cable-to-cable coupling[9]

A computer program to predict the harmonic voltage distortion caused by lower frequency harmonics[10]

Some detailed hybrid computer models for some power system components[11,12,13]

Other tools in the process of being developed include the work sponsored by NAVSEA and performed at NUSC and at the University of Pennsylvania on extending the prediction and analysis methodology described in reference 7 and the EMX (an inclusive term for EMC, EMI, EMV and EMP) work sponsored by NAVELEX and managed by NOSC. The latter includes exploitation of a NASA-developed program for Modeling and Analysis of Power Processing Systems (MAPPS).[14] Because of the applicability of using these programs to reduce risks and costs in the SSBN subsystem program, a summary of the MAPPS program is provided as appendix A. Better measuring techniques are also needed for gathering data on electronic system characteristics.[15,16] Appendix B outlines a method of determining the needed data that is compatible with analysis techniques such as those used in MAPPS.

In any SSBN subsystem approach which makes increased use of high efficiency power conversion methods, improved tools for predicting and solving electrical systems and load system integration problems are considered essential; the intuitive appreciation of problems engineers have gained with conventional systems does not apply to the high-efficiency systems. To attenuate power source noise for example, adding convention EMI filters that are effective in conventional systems can actually make high-efficiency systems go unstable.[17] Since the proposed candidate systems are based on high-efficiency power conversion methods, risk reduction through cost-effective, timely modeling and analysis is needed in the conceptual phase of the program, when decisions have the major impact on eventual total program costs.

8NAVSHIPS 0900-006-5150, Ship Design Computer Program—Ships Electrical Power Analysis and List of Power Consuming Equipment

9NAVSHIPS 0967-LP-283-5010, Handbook of Shipboard Electromagnetic Shielding Practice, section 6, prepared by the Naval Underwater Systems Center, New London, for Naval Ship Engineering Center, 1 March 1968, Change 5, December 1977

10NUSC Technical Memorandum, 344-477-76, Prediction of Total Harmonic Distortion on Shipboard Power Systems

11NSRDC Report 27-572, Simulation of Model 4580 Power Supply Set, by DW Baker and DB Boswell, February 1974

12NSRDC Report PAS-75-23, Simulation of the 750-kW Ship's Service Turbine-Generator Set Aboard DE 1052 Class Ships, by DB Boswell and DV Cowger, July 1975

13DTNSRDC Report PAS-75-15, Induction Motor Computer Simulation and its Application to the High Pressure Brine Pump, Motor, and Controller, by DW Baker and WF McMillan, November 1975

14NASA Contract NAS 3-18918, Modeling and Analysis of Power Processing Systems

15NOSC (NELC) TN 2936, Susceptibility of Electronic Equipment to Power Source—Tests on AN/SRC-31, by E Kamm and TA Danielson, 16 July 1975

16Georgia Institute of Technology Technical Report 1725-2, Power Susceptibility Test Planning for AN/SPG-55B Radar, by E Kamm (NOSC), JJ Heckman, EE Donaldson, and JA Scheer, October 1975

17RD Middlebrook, Input Filter Considerations in Design and Application of Switching Regulators, IEEE Industry Applications Society Annual Meeting, Chicago, 11-14 October 1976

DESCRIPTION OF CANDIDATE SYSTEMS

Two basic candidate systems are proposed (see fig 6). They are identical in that switching-mode power supplies accepting high voltage dc (either 160 or 270 V dc) are used for all power conversion in the electronic systems. These switching-mode power supplies are smaller and lighter than conventional 400 Hz power supplies. Each configuration has a dc link to provide continuity of power for critical loads.

The configurations differ in that configuration I (fig 6) is designed for an SSBN whose primary power source is dc, whereas configuration II is designed for an SSBN whose primary power source is ac. In addition to the switching regulator power supply's dc-to-dc conversion stage, configuration II requires an ac-to-dc power conversion stage, which can be part of either the electric power system (configuration IIA) or the electronic system (configuration IIB).

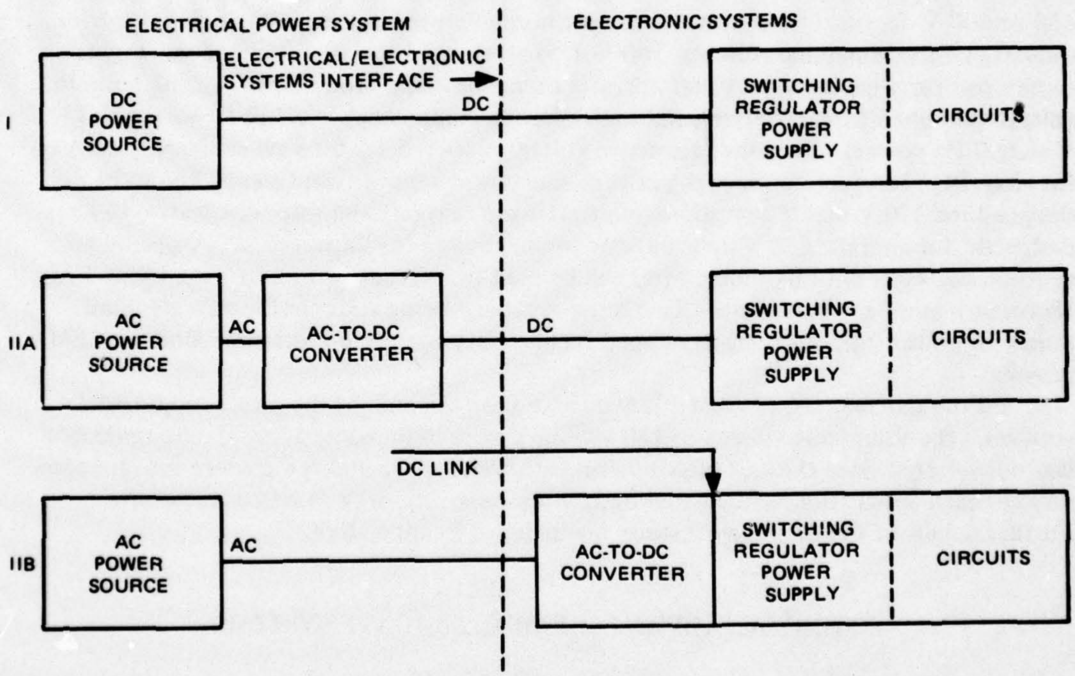


Figure 6. Candidate systems.

SWITCHING REGULATOR POWER SUPPLIES

The switching regulator power supplies being considered are similar to commercial off-line switching regulators that are widely used for low-voltage (5–50 V dc) power supplies. They use transistor switches and are readily available in power levels sufficient to power the electronics in a standard 6-foot Navy equipment cabinet. Their power conversion frequencies are 20 to 30 kHz but can be extended to 100 kHz or greater with present technology. For high voltage (up to 50 kV) and high current (100–1000 A), transistor or thyristor

power-supply designs similar to some presently being used by the Navy are proposed. The power conversion frequencies of 5 to 15 kHz at which these designs generally operate can probably be extended to 20 kHz or higher with present technology.

DC VOLTAGE TRADE-OFF

The initial selection of candidate dc voltages for distribution to electronic loads was made from voltages that either were existing dc standards or could be obtained by direct rectification of ac standards. The standard dc voltages are 28 V dc (aircraft, land vehicles, and small boats), 115 V dc (ships), 270 V dc (aircraft), and 180 to 355 V dc (submarine battery). The standard ac voltages directly rectified yield dc voltages of 160 V dc (115 V ac ship, aircraft and commercial), 270 V dc (3-phase 4-wire 115/200 V aircraft power), 300 V dc (220 V ac commercial), 550 V dc (230/440 V ac double voltage aircraft), and 600 V dc (440 V ac ship). Weight considerations eliminated 28 V dc and offered little advantage at 550 or 600 V dc, since these voltages are not normally used in the technology being considered. Of the remaining voltages, 160 V dc is attractive because virtually every power-supply company has a product that operates or can be easily modified to operate from this voltage (obtained from rectifying and peak filtering commercial single-phase power at 115 V ac 600 Hz power). The other attractive voltage, 270 V dc, is the new standard voltage for aircraft. Therefore, many high-performance power supplies can be expected to be designed for 270 V dc. It also allows multiplatform (aircraft and ship) electronics to be designed: for aircraft, 270 V dc is directly provided; and for ships, the 270 V dc and an ac-to-dc converter with harmonic filter can be used to interface with 440 V ac, 60 or 400 Hz (or any other ac) ship power. This is the approach being taken in the new standard family of power supplies being developed for the Navy Standard Electronic Module (SEM) program.

For these reasons, 160 and 270 V dc have been selected as the prime candidate dc voltages. The submarine voltage of 180 to 355 V dc is in the same approximate range but was not selected since the lack of synergism with other usage makes a custom design necessary for each application, and custom designs are relatively risky as well as expensive. Further details of the dc trade-off study are included as appendix C.

POTENTIAL ADVANTAGE OF CANDIDATE SYSTEMS

The potential advantages of the candidate systems over the existing baseline system are as follows:

Less power required by electronics.

Less cooling required by electronics.

Electronics less sensitive to power source characteristics, including transients.

Electronics smaller than present 60 or 400 Hz electronics.

Electronics lighter than present 60 or 400 Hz electronics.

Electronics potentially less expensive than equivalent 60 or 400 Hz electronics.

Dc link simplifies providing continuity of power to critical loads.

Electrical power system can be optimized independent of any electronic considerations, ie frequency can be changed from 60 Hz to 200 Hz to 400 Hz to dc at any time with no impact on electronic equipment.

Power conversion in electronics can be optimized for weight, size, efficiency, cost, etc, depending only on the state of the technology and independently of the electrical power system.

Motor generators, solid-state inverters, frequency regulation, tight harmonic voltage distortion limits, etc can all be eliminated from the electrical system insofar as the electronic loads are concerned.

MAJOR DEVELOPMENTS REQUIRED

Conceptual system design is needed to identify viable system configurations, determine initial interface specifications, and determine hardware items that must be developed to implement the system design. Configurations I and IIA of figure 6 will require the development of dc circuit protection devices (solid-state or hybrid load controllers and source controllers). Configurations IIA and IIB will require that ac-to-dc converters be developed to specifications determined in the conceptual design.

Virtually all other activities that will be required are those associated with risk reduction. The necessity for risk reduction activity cannot be overstated. The intuitive design sense developed over the years by designers of conventional power conversion equipment does not apply to the high-efficiency techniques proposed here. Power source control loops will have to be stabilized for negative resistance loads. Protection devices will have to be incorporated that will operate with loads whose currents go up as the impressed voltage goes down. Unprotected switching regulators can be destroyed by low voltages as easily as by high voltages. Adding EMI filters can increase EMI instead of decreasing it and can cause the entire power system to go unstable. These phenomena do not occur in conventional power systems, and they come as a surprise to the uninitiated engineer—often during system integration, when fixes are limited and expensive in terms of cost and schedule. The most promising risk reduction activity to avoid these problems is adequate computer modeling and analysis of the conceptual system. Fortunately, cost-effective modeling of these types of systems is becoming practical.

Also required are the following risk reduction activities:

Determine the practical limits of suppressing the noise generated by regulator power supplies, and determine the sensitivity of critical circuits to these suppressed noise levels.

Determine the mechanism coupling switching regulator noise to SSBN observables, and determine the levels of the coupled noise.

Determine cost-effective test methods, compatible with modeling and analysis methods, to develop data needed for system integration.

DESCRIPTION OF LIKELY SUPPORTING ACTIVITY AND QUALIFICATIONS

Table 2 is a partial list of personnel associated with various facilities who are knowledgable about switching regulator technology, modeling and analysis of power systems, solid-state load and source controllers, and methods of reducing harmonic currents. The emphasis is on facilities with knowledge of power conversion in electronics. No attempt is made to be complete with regard to facilities whose primary involvement is with conventional power systems.

TABLE 2. TECHNOLOGY RESOURCES.

Facility	Contact	Area of Knowledge: Switching regulator technology	Modeling and analysis	Load/ source controllers	Harmonic current/ EMI	Miscel-laneous	Notes
Navy							
Naval Ocean Systems Center San Diego, CA 92152	J Foutz Code 9234 (714) 225-2752	X	X		X		Power Electronics Branch specializes in switching regulator technology as well as modeling and analysis of power processing systems from the electronic system side of the power interface.
Naval Avionics Facility Indianapolis, IN 46218	J Jentz Code 835 (317) 353-3927	X		X			Navy in-house design capability for state-of-the-art switching regulators. Developing 270 V dc load controller for NADC AAES program. Developing Navy family of standard SEM power supplies.
Naval Underwater Systems Center Newport, RI 02480	D McQueeney Code 344 (203) 442-2534		X		X		Submarine system integration EMC problems including computer analysis. Sponsor of work at University of Pennsylvania.
David Taylor Naval Research and Development Center, Bethesda, MD 20084	HR Boroson Code 278 (301) 267-2857		X		X		Hybrid computer capability to model shipboard power system components. Passive filter for harmonic current reduction.
Naval Air Development Center Warminster, PA 18794	JD Segrest Code 3043 (215) 672-9000 Ext 2406			X		X	Advanced Aircraft Electrical System (AAES), which includes a complete generator to load 270 V dc power system including 28 V dc, 270 V dc, and 400 Hz solid-state load controllers, computer control systems, and 270 V dc generator.
Naval Research Laboratory Washington, DC 20375	BJ Wilson Code 5210.3 (202) 767-3357					X	Advance test concepts for automated digital testing of aircraft.
Naval Ship Engineering Center Washington, DC 20362	FL Henrickson Code 6156D (301) 692-6062				X		Active filter for harmonic current reduction.
Government (non-Navy)							
NASA Lewis Research Center Cleveland, OH 44135	J Triner, MS 54-5 (216) 433-4000 Ext 6631	X	X	X			Government sponsor for Modeling and Analysis of Power Processing System (MAPPS) program. General state-of-the-art knowledge in field.

TABLE 2. (Continued).

Facility	Contact	Area of Knowledge: Switching regulator technology	Modeling and analysis	Load/ source controllers	Harmonic currents/ EMI	Miscel- laneous	Notes
Government (non-Navy)(Cont)							
NASA Goddard Space Flight Center Greenbelt, MD 20771	ER Pasciutti Code 711.3 (301) 982-4885	X	X				NASA in-house design capability for state-of-the-art switching regulators including use of advanced computer-aided design programs. Sponsor and user methods developed at Duke University.
NASA Jet Propulson Laboratory Pasadena, CA 91103	DK Decker, MS 198-220 (213) 354-4035	X	X				NASA in-house design capability for state-of-the-art switching regulators. User of California Institute of Technology developed analysis approach.
USAF Aero Propulsion Laboratory Wright Patterson AFB, OH 45433	RL Verga AFAPL/POD-1 (513) 255-2923	X					Knowledge of technology as used in Air Force.
USAF Avionics Laboratory Wright Patterson AFB, OH 45433	Capt RA Wakefield AFAL/AAA-2 (513) 255-2766	X					Program manager for family of standard switching regulator power supplies for Air Force.
Universities							
Duke University Durham, NC 27706	TG Wilson, HA Owens Jr (919) 684-3123	X	X				Outstanding research record over many years in developing state-of-the-art circuits and analysis techniques and developing well qualified graduate students in switching regulator technology field.
California Institute of Technology Pasadena, CA 01125	RD Middlebrook, S Cuk (213) 795-6811 Ext 1822	X	X				Recent outstanding contributions to analysis and new types of circuits with superior characteristics.
University of Pennsylvania, Moore School of Electrical Engineering Philadelphia, PA 19174	RM Showers, KA Fegley (215) 243-8123		X		X		Development of computer based prediction analysis techniques for submarine FMC problems including harmonic currents.
University of Missouri Columbia, MO 65201	RG Hoft (314) 882-3491	X					Consulting expertise in switching regulator techniques (along with Duke and CIT).

TABLE 2. (Continued).

Facility	Contact	Area of Knowledge					Notes
		Switching regulator technology	Modeling and analysis	Load/ source controllers	Harmonic currents/ EMI	Miscel-laneous	
Universities (Cont)							
Purdue University Lafayette, IN 47907	LL Ogborn (317) 493-3028	X					
University of Toledo Toledo, OH 43606	TA Stuart, AH Eltimseh (419) 537-2638	X					
University of South Florida Tampa, FL 33620	JC Bowers (813) 974-2369/ 2581		X				Modeling Power Systems Components and Analysis of systems using SUPER SCEPTRE developed at USF.
University of Toronto Toronto, Canada	SB Dewan (416) 978-2011	X					Consulting expertise in switching regulator techniques (along with Duke and CIT).
Industry							
TRW Defense and Space System Group, Redondo Beach, CA 90276	Yuan Yu (213) 535-4321	X	X				MAPPS contractor
Bell Laboratories Whippany, NJ 07981	SD Bloom RP Massey	X			X		Knowledgeable of EMI noise suppression of switching regulators.
IBM Federal Systems Division Owego, NY 13827	R Warren (607) 687-2121 Ext 2927				X		Proposed all electronic methods of reducing harmonic currents caused by off-line switching regulators operating from ac power.
Rockwell International Electronic Devices Division Anaheim, CA 92803	RM Orndorff (714) 632-1573	X	X				Silicon on sapphire large-scale integrated circuits for military environments containing both analog and digital circuits on same chip. Includes control chip for solid state load controllers, switching regulators, etc.
Boeing Aerospace Co. Seattle, WA 98124	P Leong (206) 655-1802		X				Computer modeling of complete aircraft electrical system.
RCA Government Communications and Automated Sys Div Camden, NJ 08102	F Farmer (609) 963-8000			X			28 V dc solid state load controllers for NADC AAES program.
Telephonics Huntington, NY 11743	G Altemose (516) 549-6109			X			400 Hz solid state load controller for NADC AAES program.

SUMMARY OF KEY EVENTS TO DATE

A candidate configuration for electronic system power supplies based on switching regulator technology has been shown to be a high-leverage technology for reducing size, weight, cost, power needs, and cooling needs, as well as for improving reliability and performance. The high leverage is achieved through the use of a single high-efficiency power conversion stage between the SSBN primary dc electrical power source and the electronic circuits. If primary power is ac, an additional ac-to-dc converter is needed in the system.

The basic technology is well developed, but two unknowns exist in the SSBN application: the effect on sensitive circuits of switching noise from the regulator circuits and the generation of SSBN observables when all the SSBN electronic systems (and possibly other systems) use switching mode power conversion techniques.

Because systems that use high-efficiency power conversion techniques behave radically different from conventional power conversion systems, in ways not anticipated by the uninitiated designer, a risk reduction approach based primarily on analysis rather than experience is indicated. Computer based modeling and analysis programs that can do this type analysis cost-effectively are just becoming available. Most of a system's life-cycle costs have been shown to be established by the decisions made in the concept phase. Risk reduction through modeling and analysis is, therefore, most effectively applied when started early in the concept stage.

Preliminary information, not reported here, has been gathered on the noise susceptibility of SSBN low-frequency communication systems and on advanced techniques for reducing noise in switching regulator power supplies.

SUMMARY OF PLAN FOR FURTHER ACTION

The plan for continuing the candidate system development follows:

1. Determine the practical lower limit of noise characteristics of switching mode regulators and the effect of that level of noise on sensitive circuits and on SSBN observables.

2. Develop conceptual designs based on the proposed configuration.

3. Collect analysis tools and identify the expertise needed to evaluate the conceptual designs.

4. Evaluate the conceptual designs for efficiency, size, weight, synergism with technology, cost, reliability, continuity of power, performance, and methods for controlling harmonic current, structure currents, EMI, and observables.

5. Select conceptual design that best suits the overall SSBN technology program objectives.

6. Specify system blocks and critical interfaces such as system voltages, tolerances, control loop dynamics, and protection philosophy.

7. Identify the degree of development needed for system blocks, with emphasis on long lead-time items that are needed in several blocks (eg, load controllers).

8. Determine the cost benefit of the proposed approach over the cost of the baseline approach for one or more key SSBN electronic subsystems.

REFERENCES

1. NOSC Technical Document TD 107, Reduction of Shipboard 400-Hz Power Requirements–Cost and Technological Feasibility, by E Kamm and J Foutz, 16 May 1976.

2. NASA CR-135072 (TRW 26629.000), Development of a Standardized Control Module for Dc-to-Dc Converters, by Y Yu, RI Iwens, FC Lee, and LY Inouye, Contract NAS 3-18918, 30 August 1977.

3. RD Middlebrook and S Cuk, Modelling and Analysis Methods for Dc-to-Dc Switching Converters, IEEE International Semiconductor Power Converter Conference, Orlando, Florida, 28–31 March 1977.

4. Chief of Naval Development, Naval Technology Projections, Part III, Advanced Systems Concepts, Improved Continuity of Shipboard Power, 1 October 1971.

5. NOSC TN 270, Simplifying a Difficult Harmonic Problem, JR Wilts, 31 October 1977. (NOSC TNs are informal documents intended chiefly for internal use.)

6. NOSC TD 108, Project Manager's Guide, p I-1, by JH Townsend, 1 June 1977.

7. NAVSHIPS 0900-078-1010, TRIDENT Submarine Command and Control System EMC Control Plan, section 6 and appendix C, Rev C, 10 October 1975.

8. NAVSHIPS 0900-006-5150, Ship Design Computer Program–Ships Electrical Power Analysis and List of Power Consuming Equipment.

9. NAVSHIPS 0967-LP-283-5010, Handbook of Shipboard Electromagnetic Shielding Practice, section 6, prepared by the Naval Underwater Systems Center, New London, for Naval Ship Engineering Center, 1 March 1968, Change 5, December 1977.

10. NUSC Technical Memorandum 344-477-76, Prediction of Total Harmonic Distortion on Shipboard Power Systems.

11. NSRDC Report 27-572, Simulation of Model 4580 Power Supply Set, by DW Baker and DB Boswell, February 1974.

12. NSRDC Report PAS-75-23, Simulation of the 750-kW Ship's Service Turbine-Generator Set Aboard DE 1052 Class Ships, by DB Boswell and DV Cowger, July 1975.

13. DTNSRDC Report PAS-75-15, Induction Motor Computer Simulation and its Application to the High Pressure Brine Pump, Motor, and Controller, by DW Baker and WF McMillan, November 1975.

14. NASA Contract NAS 3-18918, Modeling and Analysis of Power Processing Systems.

15. NOSC (NELC) TN 2936, Susceptibility of Electronic Equipment to Power Source–Tests on AN/SRC-31, by E Kamm and TA Danielson, 16 July 1975.

16. Georgia Institute of Technology Technical Report 1725-2, Power Susceptibility Test Planning for AN/SPG-55B Radar, by E Kamm (NOSC), JJ Heckman, EE Donaldson, and JA Scheer, October 1975.

17. RD Middlebrook, Input Filter Considerations in Design and Application of Switching Regulators, IEEE Industry Applications Society Annual Meeting, Chicago, 11–14 October 1976.

APPENDIX A
MODELING AND ANALYSIS OF POWER PROCESSING SYSTEMS (MAPPS)

The MAPPS program is summarized by providing both a copy of the introduction to the proposal for continuation of Phase II of the program (now under contract) and selected Vu-graphs presenting Phase IIA results. NOSC, as part of the NAVELEX sponsored EMX program, is collecting and documenting the MAPPS subprograms and similar subprograms from various sources, thereby making them easily available to the Navy technical community and Navy contractors. An opportunity exists to have the SSBN subsystem technology program be one of the first effective users of these programs for Navy purposes. Exercising this opportunity to reduce risks is strongly recommended.

INTRODUCTION TO THE PROPOSAL FOR CONTINUATION OF PHASE II OF THE PROGRAM

Electric power processing is a complex field encompassing power and control electronics, magnetics and semiconductor devices, and nonlinear feedback control. However, due to the industry's preoccupation with hardware production, the technology development has been hampered by the lack of vigorous modeling, analysis, design, and optimization techniques. Consequently, heavy reliance on empirical and intuitive methods has become necessary in the design of power processing equipment. Needless to say, such inadequacies inevitably lead to penalties involving equipment performance, weight, reliability, and cost. In view of the following factors,

(1) The forthcoming use of considerably higher level of power in future power processing equipment,

(2) The prevailing trend of equipment standardization which must relay on analysis-based design, and

(3) The ever-increasing sensitivity to equipment development cost,

in which brute-force and single-minded power processing design would only result in more severe penalties than ever incurred, the need for a power-processing modeling and analysis program cannot be overemphasized.

To fulfill such a need, phase I of a program entitled "Modeling and Analysis of Power Processing Systems (MAPPS)" was initiated in 1973, in which the feasible methodology for the MAPPS approaches was formulated. Subsequently, the program entered phase II in 1975, during which certain selected approaches were implemented through various computer-based subprograms dealing with the power processing design, analysis, and optimization at the equipment level. The framework of an expandable Data Management Program was also completed within the initial phase II to provide the basic coordination for the various subprograms. Being of long-range nature, the program is currently at the conclusion of the initial phase II.

This proposal provides the technical details through which TRW plans to expand the MAPPS subprograms in the phase II continuation effort. The expansion will be centered on three major categories: Power Processor Performance Analysis and Simulation, Power Circuit Design Optimization, and Control Circuit Design Based On Performance

Specifications. The analytical approaches to each subprogram category will be based on those already identified and practiced during the initial phase II. The expansion effort will realize the MAPPS program goal of enabling ready subprogram applications by users interested in power processor design and analysis.

In addition, TRW will include in the phase II continuation effort the inception of a subprogram specifically oriented to Navy EMC related power processing problems. It has always been NASA's as well as TRW's intention to extend MAPPS' application into other government/industry concerns. Consequently, TRW is pleased with the possible joint NASA-NAVY sponsorship, which attests to the program's growing popularity and hopefully leads the way to the eventual realization of a truly prevalent MAPPS program.

The Technical Proposal, Volume I, presents TRW's Statement of Work, Technical approach, program-related facilities, manpower estimates, program schedule, related experiences, and management plan with resumes of key personnel. Pricing data and contractual provisions are contained in Business Proposal, Volume II.

SELECTED VU-GRAPHS PRESENTING PHASE IIA RESULTS

MODELING AND ANALYSIS OF POWER PROCESSING SYSTEMS (MAPPS)

(NAS 3-19690)

Presentation at

NASA LEWIS RESEARCH CENTER
CLEVELAND, OHIO

by

TRW DEFENSE AND SPACE SYSTEMS
REDONDO BEACH, CALIFORNIA

February 3, 1977

SECTION 5

OVERALL MAPPS PROGRAM OBJECTIVE

The MAPPS overall objective is to provide the modeling and analysis tools to enable realistic conceptual design and tradeoff studies and to reduce the design, analysis, and development time, and thus the cost, in achieving the required performances for power processing equipment and systems.

SECTION 2

DEFINITION OF COMMONLY-USED TERMS

Component:	Electronics parts such as magnetics, capacitors, semiconductors, etc.
Equipment:	A black box to satisfy certain input/output compatibility, such as a line regulator, a DC to DC converter, etc.
System:	A combination of many equipments aimed to fulfill the source/load compatibility of a given spacecraft.
Performance:	Steady-state or transient behavior of the equipment or system.
Design:	Conceive a scheme for equipment or system to meet a given set of performance requirements.
Analysis:	Analytically/numerically determine the performance of a given design.
Design Optimization:	To design equipment or systems and concurrently to minimize some defined parameters (such as weight or loss).

SECTION 2 (Cont'd)

Performance Requirement Categories

Control-Independent Performance Requirements

These requirements are closely associated with the power circuit design.

- Source EMI
- Output ripple
- Weight
- Loss
- Input/output voltage levels
- Load power

Control-Dependent Performance Requirements

These requirements are closely associated with the control-circuit design.

- Stability
- Attenuation of source sinusoidal disturbances (audio susceptibility)
- Response of load sinusoidal disturbance (output impedance)
- Response to step line change
- Response to step load change
- DC regulation

SECTION 6

MAPPS SUBPROGRAMS & SPECIFIC OBJECTIVES

Subprograms		Objectives
Design Optimization Subprograms	(DOS)	Power Circuit Design
Control Design Subprograms	(CDS)	Control Circuit Design
Performance Analysis Subprograms	(PAS)	Regulator Performance Analysis
System Analysis Subprograms	(SAS)	System Configuration & Analysis
Component Library Subprograms	(CLS)	Component Selection
• Dedicated Special Subprograms	(DSS)	Magnetics-Semiconductor Switching Phenomena
• Cost & Reliability Subprograms	(CRS)	Cost and Reliability Prediction & Analysis

*Not included in Phase II

6.1 Design Optimization Subprogram

Utility: Allow one to conceive a design to meet all control-independent performance requirements, and concurrently optimize a certain design quantity deemed particularly desirable.

Category: Components (magnetics)
Circuits
Equipment

Expectation: Optimum power circuit design and switching-frequency selection, including values and ratings of all power components.

Phase II Accomplishments:

Inductor and transformer design optimization
Input filter design optimization
Buck switching regulator design optimization

6.1.2 Basic Optimization Techniques

- Derive close-form optimum solutions using the method of Lagrange Multipliers

- Obtain numerical optimum solution using nonlinear programming techniques

  Reduced Gredient Method: GRG code
  Penalty Function Method: SUMT code

6.2 Control Design Subprogram

Utility: Allow one to perform a control-circuit design based on a given set of control-dependent performance specifications. The power circuit and the switching frequency are assumed given.

Category: Network synthesis based on standardized circuit using S-transform.

Expectation: Confident design prior to or without breadboarding.

Reduce "bench-design" effort during breadboard stage

Phase II Accomplishment:

Conceive single-loop standard error processor

Buck regulator control circuit design using standard error processor.

6.3 Performance Analysis Subprogram

Utility: Allow one to predict control-dependent performance characteristics of a given equipment design.

Category: Continuous frequency domain converter performance analysis.

Worst-case performance analysis

Discrete time domain converter-performance analysis

Discrete-time domain cost-effective simulation

Expectation: Accurate equipment control-dependent performance prediction including worst-case analysis

Phase II Accomplishment:

Establish analytical and computational tools for all categories.

Implement three PAS's for single- and multiple-loop controlled converters.

6.4 System Analysis Subprogram

Utility: Provide power processing system engineers with design and tradeoff tools.

Category: System configuration design

System performance analysis (dynamic intra-system interactions)

Expectation: Allow a more "scientific" system configuration design and determination of system equipment specification and requirements by minimizing the need for subjective bias from the system engineer.

Develop methodology for dynamic system performance analysis/simulation.

Phase II Accomplishments:

Configuration design for a source-line regulator system.

Cost-effective simulation for a 12th order system.

6.5 Component Library Subprogram

Utility: To allow a User to select a commercially-available component closely matched to requirements dictated by the circuit design.

Category: The following data bases are the general categories:

Magnetic cores
Wire
Capacitors
Resistors
Semiconductors

Expectation: A continually-updated component data bank used in support of various MAPPS subprograms and in particular, the design optimization subprogram (DOS).

Phase II Accomplishments:

Inductor powder core
Magnet wire
Foil tantalum capacitor
Polycarbonate capacitor
Wire-wound resistor

SECTION 7

MAPPS CAPABILITY AND ITS FUTURE

7.1 What MAPPS Can and Cannot Do Eventually

CAN DO:

- * Detailed power circuit design optimization to meet given specifications.
- * Basic control circuit design to meet performance requirements.
- * Analyze all performance, nominal and worst-case, on equipment level.
- ** System performance and failure mode effects.
- ** Identification of optimum system configuration.
- ** Retrieve best-fit components per User's instruction.
- ** Magnetics-semiconductor switching phenomena analysis.
- Reliability analysis.
- Analysis of recurring cost.

CANNOT DO:

- Grounding Philosophy and noise suppression.
- Protection Philosophy (standardization).
- Details of logic design (standardization).
- Mechanical design.

* Can be completed in Phase III with sufficient support.
** Continued in Phase III.

7.2 What Do We See as MAPPS Future?

- Fully implemented and continuously-maintained data management program.
- Fully automated analysis of performance for all basic DC-DC converters in two years.
- Fully automated design for the basic DC-DC converter power and control circuits to meet performance specifications in three years.
- Elimination of breadboard development stage in four years (High-Voltage, High-Power magnetics not included).
- Computer-aided power system configuration design and dynamic interaction analysis/simulation in five years.
- Meaningful reliability and cost analysis in five years.
- Significant cost saving, weight and efficiency optimization, worst-case design, and reliability improvements for NASA and other power processing equipment or system development programs.

SECTION 9

CONCLUSIONS

1. The methodologies of modeling and analysis in power processing are all established.

2. Design, analysis, and optimization of basic converter-regulators are on their way to be available for all power processing designers.

3. Cost-effective system configuration study and system disturbance propagation are becoming a reality.

4. An expandable data management program intended for User's convenience in using the power processing subprograms is demonstrated.

5. Many subprograms are now applicable for utilization by power processing "designers." With full support in next phase, the MAPPS should become a compatible partner to all "designers" interested in power circuit design optimization, control circuit design, equipment performance analysis, system configuration tradeoff, and analysis of system interaction.

APPENDIX B
NEW TEST METHOD TO DETERMINE EQUIPMENT DATA NEEDED FOR SYSTEM ANALYSIS AND SYSTEM INTEGRATION

DATA (GO/NO-GO) AVAILABLE IN EXISTING SYSTEM

Usually, only limited data (go/no-go) are obtained about the type of power needed by the electronic load. MIL-STD-1399, section 103, specifies three types of power available for shipboard electronic equipment. Type I is preferred but Types II and III are more closely regulated. Each type of regulation denotes different tolerances for powerline characteristics such as voltage, frequency transients, and harmonics. For example, Type I steady state voltage is delivered within ±5% of its nominal value, Type II within ±1%, and Type III within ±½%.But the reason Type III power is specified for a piece of equipment may be unknown. The equipment, for example, may be unable to tolerate either a less regulated frequency or a particular voltage transient or some other power-line characteristic.

More definitive go/no-go data are available from MIL-STD-461 power-lead tests. These test indicate that the equipment's emission and susceptibility characteristics are within the specified levels (if no exceptions are taken).

IMPROVED TEST METHODOLOGY

The susceptibility test methodology is depicted in figure B1. First, one powerline characteristic is varied at a time while the output parameters are continually monitored until degradation is detected. Second, if more than one characteristic causes a particular output parameter to degrade, then two or more characteristics are varied simultaneously to detect the degradation.

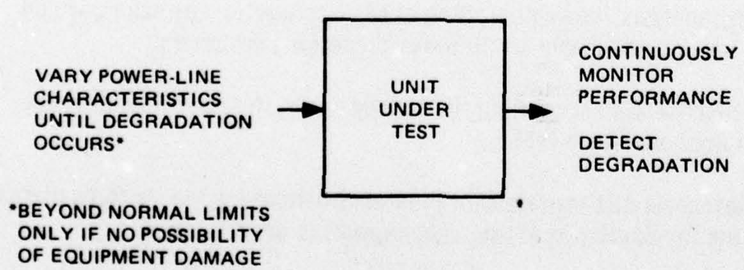


Figure B1. Susceptibility of electronics to power source–new test method.

The power-line characteristics to be varied are as follows:

- Steady-state frequency
- Frequency modulation
- Frequency transients
- Steady-state voltage–balanced and unbalanced
- Voltage modulation
- Voltage transients
- Harmonic distortion voltage
- Power interruption time

These characteristics are defined in MIL-STD-1399, section 103, for three types of ac power for operation of shipboard electronics.

Table B1 lists examples of parameters monitored for degradation. Each unit under test will have different parameters monitored, as determined by personnel familiar with the critical parameters and susceptible modes of operation.

TABLE B1. EXAMPLES OF PARAMETERS MONITORED FOR DEGRADATION.

AN/SRC-31 Radio	AN/SPG-55B Radar
Transmitter–AM voice mode	Track transmitter–long and narrow pulse mode
Carrier power output	Modulator current
Peak modulated power output	Peak network voltage
Modulation distortion	Klystron beam current
Transmit frequency	Waveguide fault
Transmitter–FSK data mode	Ion fault
Power output	Focus power supply fault
Transmit frequency	Output power
Modulation frequency shift	Output frequency
Receiver–AM and FSK modes	Detected pulse
Sensitivity	Cw transmitter–illuminating and Doppler modes
Receive frequency	Klystron beam current
	Klystron beam voltage
	Body current
	Focus current
	Output power
	Output frequency
	AM/FM spectrum

Figure B2 is an example of a two-dimensional plot for susceptibility data (the results of one of the susceptibility tests on the AN/SRC-31 radio). Plots will also be multidimensional if more than one power-line characteristic is varied at a time.

The following information is generated by the test methodology:

Graphs of electronics' susceptibility to power source variations

Effect on power source by loading it with electronics

Impedance of test power source

In addition to susceptibility data, measurements are also taken to determine power-line emission data from the electronics. Also, measurements are taken to determine the impedance of the test source. With knowledge of the test source impedance, calculations can be made to predict the equipment's performance aboard ship (with knowledge of shipboard source impedance).

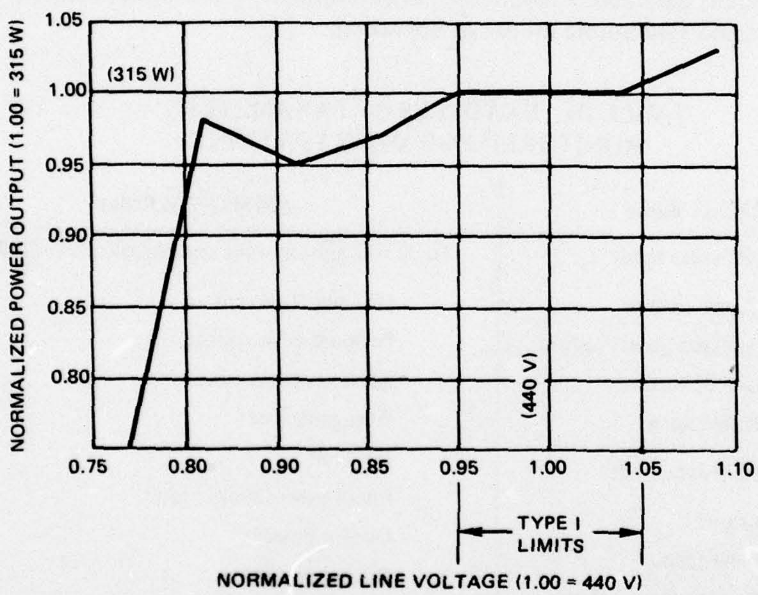


Figure B2. Susceptibility of transmitter power to line voltage for a AN/SRC-31 radio in FSK data mode.

SYSTEM DESCRIPTION FOR AUTOMATIC TEST

A potential input power data acquisition system is shown in figure B3. A single-period sinusoidal waveform with the desired harmonic distortion is generated by the data acquisition processor (DAP) as a sequence of 150 10-bit digital words. (This allows reproduction of the 25th harmonic with reasonable fidelity.) This sequence is then stored in a random access memory (RAM). The DAP sets the clock, for example, for a nominal 400 Hz output (60 kHz), sets the scaling amplifier for the nominal voltage output, and initiates the

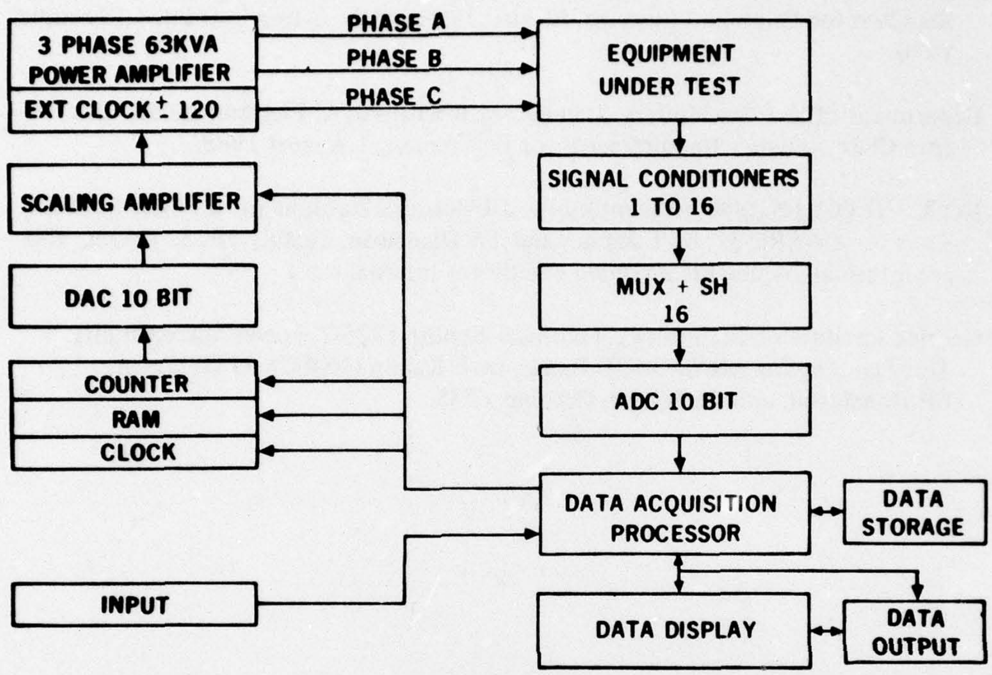


Figure B3. Input power data acquisition system.

counter. The counter loops continually through the 150 words in the RAM. The data words are input to a digital-to-analog converter (DAC) which outputs a sinusoidal waveform with the desired harmonic content. This is shifted to form three phases, amplified, and applied to the equipment under test (EUT). Frequency can be varied on a transient or steady-state basis by digital control of the clock rate. Amplitude may likewise be varied by digital control of the scaling amplifier.

Up to 16 outputs can be monitored at one time. The outputs are first conditioned for the analog-to-digital converter (ADC) and then channeled into the DAP through 16 MUX and SH channels.

The DAP processes the data under software control and displays the data in the form of multivariable parameter displays that allow the degradation of the EUT to be observed as a function of power source parameters (voltage, frequency, harmonic content, etc). Raw data are stored for off-line processing and display so that they are always available for system integration purposes and, if required, computer modeling of the system.

APPENDIX B BIBLIOGRAPHY

1. Department of the Navy Military Standard MIL-STD-1399, section 103, Interface Standard for Shipboard Systems, Electric Power, Alternating Current, 1 December 1970.

2. Department of Defense Military Standard MIL-STD-461A, Electromagnetic Interference Characteristics Requirements for Equipment, 1 August 1968.

3. NOSC (NELC) TN 2946, Susceptibility of Electronic Equipment to Power Source - Tests on AN/SRC-31, by E Kamm and TA Danielson, 16 July 1975. (NOSC TNs are informal documents intended chiefly for internal use.)

4. Georgia Institute of Technology Technical Report 1725-2, Power Susceptibility Test Planning for AN/SPG-55B Radar, by E Kamm (NOSC), JJ Heckman, EE Donaldson, and JA Scheer, October 1975.

APPENDIX C
HIGH-VOLTAGE DC SYSTEM TRADE-OFF STUDY

In the existing baseline power system, the 60 Hz source voltage is converted to high-voltage dc, and then for many electronic loads this dc voltage is reconverted to 400 Hz ac. Within almost all of these loads, the 400 Hz ac is again converted back to low-voltage dc. Thus, most of the dc-to-400 Hz ac conversion (requiring seven motor-generator sets) is unnecessary.

If the conversion to 400 Hz is eliminated, a question arises: What is the most preferable dc voltage level for the distribution of power? The existing dc voltage level is nominally 250 volts (180 to 355 V dc), which may or may not be the best choice for the candidate system from the electronic load viewpoint.

To determine the preferred dc voltage, the first criterion considered is the availability of electronic equipment either already in use or planned for the future. Some equipment that requires dc input is available for platforms with dc voltage sources and, therefore, common dc voltages on various platforms are identified. For equipment requiring ac input, off-line switching regulators are being used more and more. These regulators can already use or can easily be adapted to use the dc voltage levels obtained after direct rectification and filtering of the ac. These dc levels, therefore, are identified for common ac voltages available on various platforms.

For these identified preferred voltages, then, a trade-off study is performed using copper-weight and copper-cost criteria, with consideration given to insulation cost, cable strength, and transistor technology.

CANDIDATE DC VOLTAGES

The candidate dc voltages are derived from power sources available on various platforms. The Navy platform power sources are identified and their specifications are discussed in NOSC (NELC) TN 2599.[1]

28 V DC

Navy platforms supplying power at 28 V dc include aircraft, manpack equipments and military vehicles. Therefore, much electronic equipment is available that is powered by 28 V dc. Also it is less costly to transform 28 V (rather than a higher voltage) to the lower voltages (eg 5 volts) required by many digital circuits.

Thus 28 V dc is a candidate voltage (see figure C1).

160 V DC

Voltages close to 160 V dc result when single-phase 115 V ac is bridge rectified and peak filtered, and also when three-phase 115 V ac is bridge rectified and either peak or

---

[1] NOSC (NELC) TN 2599, Input Characteristics of a Universal Input Power Supply for Navy Multiplatform Usage, by J Foutz, 1 April 1974

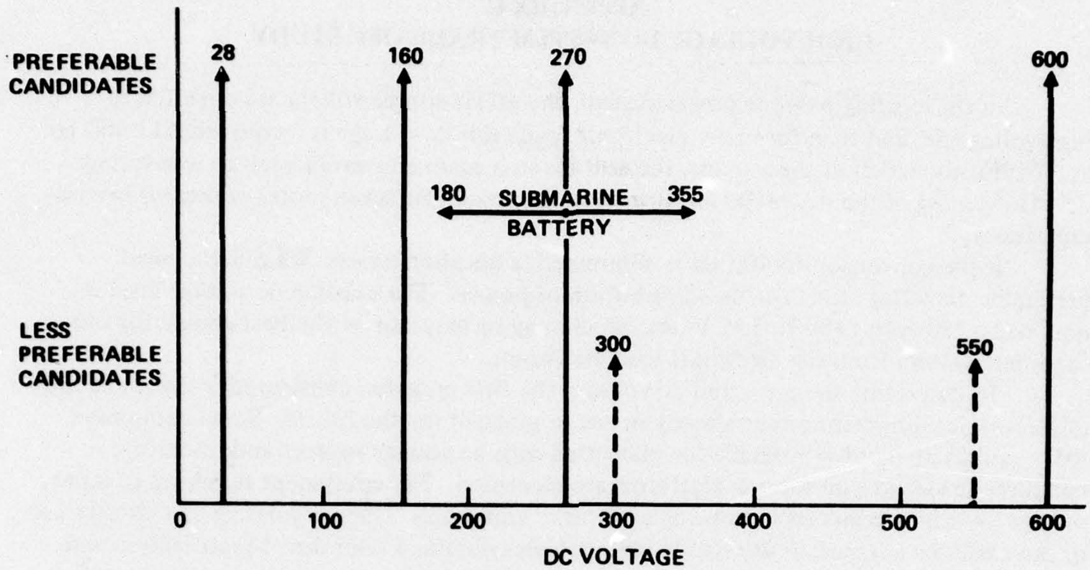


Figure C1. Dc voltage candidates for SSBN power systems.

averaged filtered. Peak filtering occurs with infinitely-capacitive input filters and therein would deliver $115\sqrt{2}$ V dc (= 163 V dc).[1] Average filtering occurs with infinitely-inductive input filters and therein would deliver $\left(\frac{3}{\pi}\right)$ 115 V dc (= 155 V dc).[2] Although these conditions are purely theoretical, they closely represent many applications in which there is considerable inductance or capacitance in the load circuit. Similar calculations were performed for the dc voltages that follow, and the results are listed in table C1.

Navy platforms supplying 115 V ac include shore installations, ships, manpack equipments, and aircraft (one phase only). Also, 115 V ac is a common commercial power source voltage both in the US and some parts of Europe. Therefore electronic equipment powered by 115 V ac is readily available. In many cases, these equipments could be adapted to accept 160 V dc with minor modifications.

Thus 160 V dc is a candidate voltage.

270 V DC

270 V dc is derived by rectifying three-phase 115/200 V ac. Navy platforms supplying thee-phase four-wire 115/200 V ac include aircraft, ships (for aircraft servicing and avionics), and shore installations. Also, the new Advanced Aircraft Electrical System (AAES)[3] will supply 270 V dc as the primary power source voltage in one configuration. Using 270 V dc for ships as well as aircraft will ease the design of multiplatform electronics.

Thus 270 V dc is a candidate voltage.

---

[2]Schaeffer, Rectifier Circuits: Theory on Design, Wiley, 1965

[3]OR-WSL04, Operation Requirements (OR) for Advanced Aircraft Electrical System (AAES), 8 July 1975

TABLE C1. CANDIDATE DC VOLTAGES DERIVED FROM BRIDGE-RECTIFIED AND FILTERED-AC VOLTAGES.

Bridge-rectified ac voltage	Dc voltage		Candidate dc voltages
	Peak (capacitive) filtered	Average (inductive) filtered	
115 single-phase	163	104	160
115 three-phase	163	155	160
115/200 three-phase four-wire	282	269	270
200 three-phase	311	297	300
230/400 three-phase four-wire	565	540	550
440 single-phase	622	397	600
440 three-phase	622	594	600

300 V DC

300 V dc is derived by rectifying 220 V ac. Navy platforms do not generally supply 220 V ac, but this voltage is common in many European countries such as Germany, France and Switzerland,[4] and off-line power supply designs are available for it.

Thus 300 V dc is a less preferable choice as a candidate voltage.

550 V DC

550 V dc is derived by rectifying 230/400 V ac. Several studies have advocated use of these ac voltages for avionics (double the voltage of 115/200 V ac.[4] The XB-70 and B-1 aircraft successfully used this double voltage,[5] but it is not widely used in this country. It is commonly used in England.[4]

Thus 550 V dc is a less preferable choice as a candidate voltage.

600 V DC

600 V dc is derived by rectifying 440 V ac. The only Navy platforms supplying 440 V ac are ships. However, all ship service power is generated as 450 V ac (440 V ac at user terminal). Therefore 440 V ac, three-phase is preferred on all ships including submarines (MIL-STD-1399), section 103).[6]

[4] US Dept of Commerce, Electric Currents Abroad, July 1967

[5] North American Rockwell Electronics Group Report C71-1148/401, Trends in Electrical Power Systems, J Foutz, 22 December 1972

[6] Department of the Navy Military Standard MIL-STD-1399, section 103, Interface Standard of Shipboard Systems, Electric Power, Alternating Current, December 1970

Thus the choice for the preferred dc voltage is narrowed by identifying four preferences: 28 V dc, 160 V dc, 270 V dc, and 600 V dc.

TRADE-OFF STUDY TO DETERMINE BEST CANDIDATE(S)

To determine the best choice of the preferred voltages, a trade-off study was performed in which the criteria used were insulation costs, cable strength, transistor technology, and weight and cost of the copper in the distribution cables.

First, the resistances (R) of the copper cables were calculated under the following assumptions: the power (P) delivered is 1 kW, the power factor is 1, and the maximum voltage drop in each cable is 5%. Then,

$$P = EI$$
$$= 10^3 \text{ watts,}$$

where E is the voltage and I is the current. Thus, $I = 10^3/E$, and, for a 5% voltage drop,

$$R = 0.05E/I$$
$$= \frac{0.05E^2}{10^3} \text{ ohms.}$$

Resistances were calculated for the four preferred dc voltages and these are shown in table C2 (second column).

Standard copper cable sizes were then selected whose resistances are close to but less than the calculated resistances, thereby keeping the voltage drops under 5% (see columns 3 and 4 of table C2). For 600 V dc, however, the selected gauge size (#20) was larger than required. It was assumed that the closest standard size (#22) would not be strong enough for this application. (The individual wire diameter of #22 stranded cable is typically 0.010 inch.)

Table C2 also lists the cable diameters, copper weight, copper cost, and power loss for the four selected cable sizes. Although the weight and cost of copper vary widely, the power loss, as expected, varies only slightly. In fact, the power losses would be identical if the cables could be chosen to have resistance values exactly as calculated (to give 5% voltage drops). For a 5% voltage drop, the power dissipated

$$Pd = 0.05EI$$
$$= 0.05P,$$

and for P = 1 kW, Pd = 50 watts.

Thus, the significant criteria are the weight and cost of copper, which are both plotted in figure C2. Although the higher voltages show progressively lower weights and costs, the relationships are not linear (note the logarithmic ordinate scale). Differences of 1004 pounds and $2171 exist between 28 V dc and 160 V dc cables, whereas differences of only 10 pounds and $21 exist between 270 V dc and 600 V dc cables. Also, if criteria such as insulation costs, cable strength, and transistor technology are considered, 600 V dc cable has many disadvantages.

TABLE C2. DC VOLTAGES VERSUS WEIGHT AND COST OF COPPER IN 1000 FEET OF DISTRIBUTION CABLE (ASSUMING 5% MAXIMUM VOLTAGE DROP).

Dc voltage	Resistance for 5% voltage drop, Ω	Resistance for 1000 feet of standard cable, Ω	Stranded copper cable size gauge number	Cable diameter, inches	Weight of copper,[1] pounds per 1000 feet	Cost of copper,[2] dollars per 1000 feet	Power loss in cable, W
28	0.039	0.03	two 3/0 (in parallel)	0.47 each	1036	2258	41
160	1.28	1.04	10	0.116	32	87	41
270	3.65	2.6	14	0.07	13	40	36
600	18.0	10.5	20	0.04	3	19	29

1. ITT, Sams & Co, Reference Data for Radio Engineering 1975, page 4-58
2. Cost data from Belden Corp, Richmond, IN, telephone quote on 1 August 1977

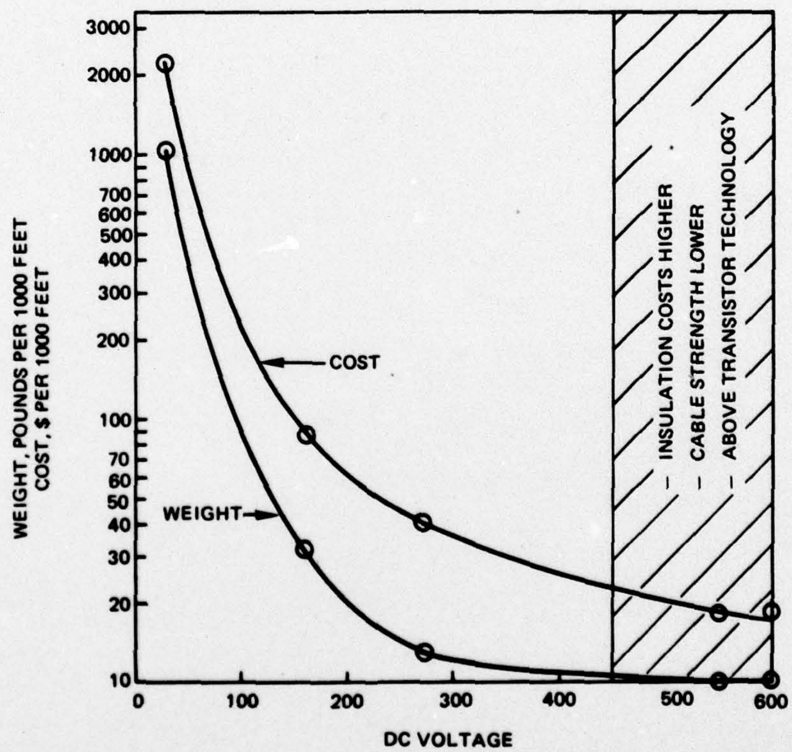


Figure C2. Dc voltages versus cost and weight of copper in distribution cables (assuming 5% maximum voltage drop).

The best choices therefore are 160 V dc or 270 V dc. This preliminary study slightly favors 270 V dc as the probable best choice because (1) the distribution cables weigh and cost less, (2) 270 V dc will be distributed on future (1980+) Navy aircraft, since it is advantageous for multiplatform electronics, and (3) a family of standard SEM power supplies are being developed that will accept 270 V dc.